REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comment regarding this burden estimates or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED FINAL Technical Report

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
A New Approach to Structural Reliability in Fatigue Failure	N00014-96-1-0631

6. AUTHOR(S)

Dr. Sia Nemat-Nasser (PI)
Dr. Joseph Zarka

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
University of California, San Diego Dept. of MAE 9500 Gilman Drive La Jolla, CA 92093-0416	97PR01513-00

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING / MONITORING AGENCY REPORT NUMBER
Office of Naval Research Program Officer Roshdy S. Barsoum ONR 334 Ballston Centre Tower One 800 North Quincy Street, Arlington, VA 22217-5660	P00001

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

20020829 015

13. ABSTRACT (Maximum 200 words)

The project objective is to develop formalism for assessing fatigue fracture of welded parts of ship structures based on a newly developed automatic Learning Expert System (L.E.S.), using extensive knowledge of material characteristics, experimental results, and results obtained through computational simulations. Any study of the welds on a ship structure must take into account the uncertainties and random characteristics of the loading, as well as the fatigue lifetime of the welds. Due to the stochastic nature of the loads, the available deterministic approaches are not sufficient to give a reliable evaluation of the structural safety. Although there has been some effort to fill this gap by probabilistic approaches, these are yet of limited usefulness because of the limited available databases. The research project will ultimately demonstrate the applicability and effectiveness of L.E.S to this class of engineering mechanics problems.

As the first and fundamental step in this project, it is necessary to build a relevant database. Experimental and field date has secured from Navy research centers, and through collaboration with scientists working in this general area. Additional data has been obtained from literature searches.

14. SUBJECT TERMS			15. NUMBER IF PAGES 18
structural reliability, fatigue failure, welded structures			16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

FINAL TECHNICAL REPORT

New Approach to Structural Reliability in Fatigue Failure

Period: April 1996 - February 2002

Contract No: N00014-96-1-0631
ONR Program Officer: Roshdy Barsoum

PI: Sia Nemat-Nasser
University of California, San Diego
Center of Excellence for Advanced Materials
9500 Gilman Drive, La Jolla, CA 92093-0416
Phone (858) 534-4914
Fax (858) 534-2727
Email: sia@shiba.ucsd.edu

Submitted: August 15, 2002

I.   Abstract

The features of welded joints not only shorten their service lives, but also make modeling of their fatigue damage complicated. Our research approach utilized the automatic learning technology to make the best use of available information in the assessment of structural reliability. Our goal was to build tools for assessing and predicting fatigue/fracture failure of structures, in particular the welded ship structures. Considerable progress has been made, albeit further improvement can be achieved.

At first, we built an organized database of experimental data and numerical analysis results that includes the possibly governing parameters in failure process. Then we extracted the mathematical relations between these parameters from the database using various automatic learning tools in a systematic way, and checked their predictive accuracy. After the mathematical relations became reliable, we applied them to new data sets to predict fatigue failure likelihood and life expectancy. This approach can be extended to new problems, and can be used to provide clues for further study of failure mechanisms.

We developed specific procedures and applied them to cruciform and beam structural details made of welded A36 steel and AL-6XN stainless steel components. To ensure the validity of the approach, different geometric configurations and materials were included. Parameters of fatigue damage, including geometry, material properties, loading history and stress field under the loading, were either collected from experimental records or generated using finite element analysis for the critical positions in the structural details. We employed a window of optimal size and focused it over the structure, wherever failure might occur. Inside the window, factors such as equivalent range of applied loading, maximum, minimum and average value of von Mises stress as well as contours of constant stresses and their spatial gradients were computed. These parameters were then put together with the recorded fatigue failures and the data sets were submitted to a comprehensive automatic learning system to extract the imbedded mathematical patterns. The obtained rules, neural networks, and statistical regression functions delivered fairly accurate predictions of dangerous areas and yielded projected fatigue lives that can be used as lower and upper bounds of the actual fatigue lives.

II. Technical Section

Research Objective

A new approach based on automatic learning and optimization techniques was used to study the reliability of ship structures and particularly the fatigue failure of the welded parts. The automatic learning technology made it possible to integrate the available knowledge of experts with the experimental results and/or numerical simulation results. The goal was to systematically build a tool for assessing and predicting fatigue/fracture failure of any part, especially weldments, of large structures subjected to any loading, through sub-structuring and using experimental database as well as computational/theoretical analyses in a unified manner. This goal has been realized to the degree that the available data permit.

Science & Technology Objective

As to our specific technological development, we have used laboratory experimental data on specific welded details for ship structures, together with systematic computational simulations, to develop mathematical formulas in terms of rules, weights and regression functions to predict whether or not given structural details, subjected to pseudo random design loading, would fail and have estimated the corresponding life expectancy. Our research work included different geometric configurations such as cruciform specimens and beams, and different materials including the stainless steels for future naval constructions. This approach delivered fairly accurate predictions of dangerous areas and yielded projected fatigue lives that can be used as lower and upper bounds of the actual fatigue lives. This

approach can be used to predict fatigue failure and the corresponding life of other details and large structures, and can be improved as more data become available.

Technical Approach I (Database Construction)

Several fatigue tests have been utilized in our approach. The first one was carried out at University of Illinois at Urbana-Champaign to investigate the *Fatigue Characterization of Fabricated Ship Details for Design* (ship structure committee report SSC-346). Experiments were performed on a typical structure using a variable load history that simulated a ship history. The selected structural detail, ship structural detail No. 20, is often used in ship and offshore structural design, and is one of the more fatigue-prone structural components. The detail No. 20 consists of a central plate and two long loading plates welded to the central plate by all-around Shielded Metal Arc Welding (SMAW) fillet welds (see figure 1). Subsequently, three experimental resources have been used to expand the scope of database. They are:

1. *Resistance of Welded Details Under Variable Amplitude Long Life Fatigue Loading,* J.W. Fisher et al; ATLSS Engineering Research Center, Lehigh University (ATLSS report 92-04).

2. *Fatigue Strength of Stainless Steel Weldments in Air,* D.P. Kihl et al; Naval Surface Warfare Center, Carderock Division, (NSWCCD-65-TR-2000/04)

3. *Fatigue Resistance of Large Welded AL-6XN Stainless Steel Components with Fillet, Groove and Attachment Welds,* J.W. Fisher et al; ATLSS Engineering Research Center, Lehigh University (ATLSS report 01-04).

The three experimental reports recorded fatigue tests on A36 steel beam, stainless steel cruciform, and stainless steel beam specimens, respectively. Basic configurations of the three experiments are shown in figure 2, 3, and 4, respectively.
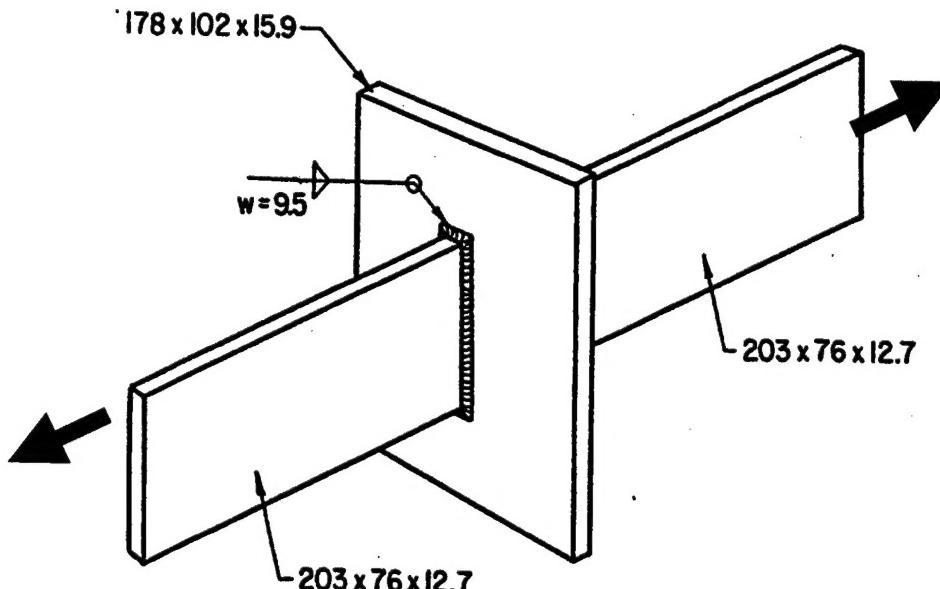

**Figure 1. Detail No. 20 sample (dimension in mm)**
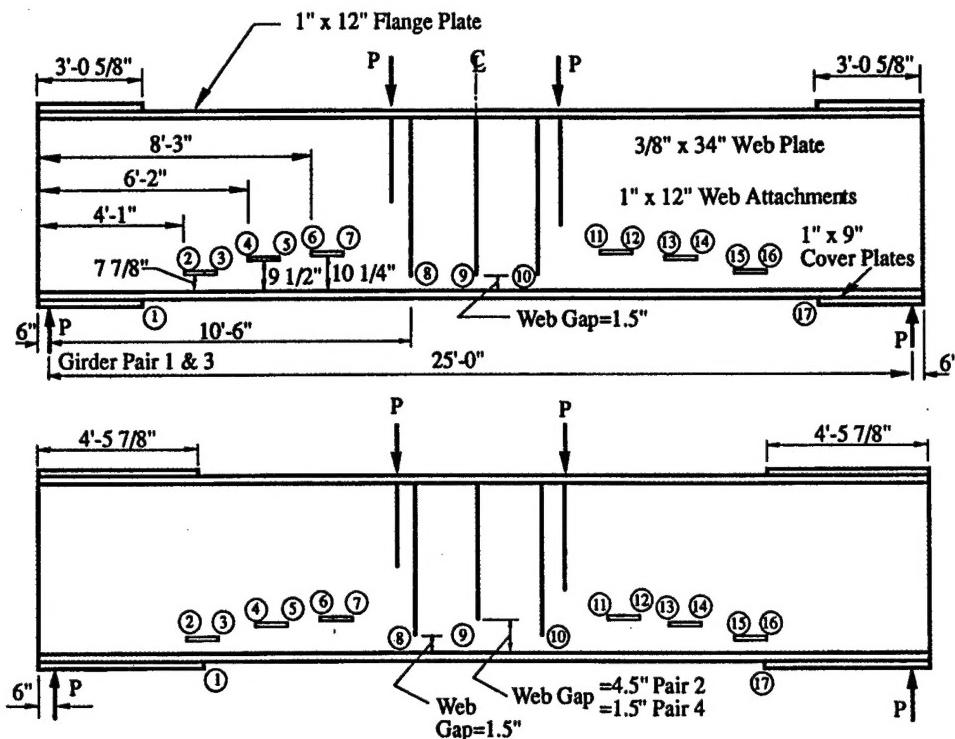
Figure 2. Schematic of A36 steel beam testing
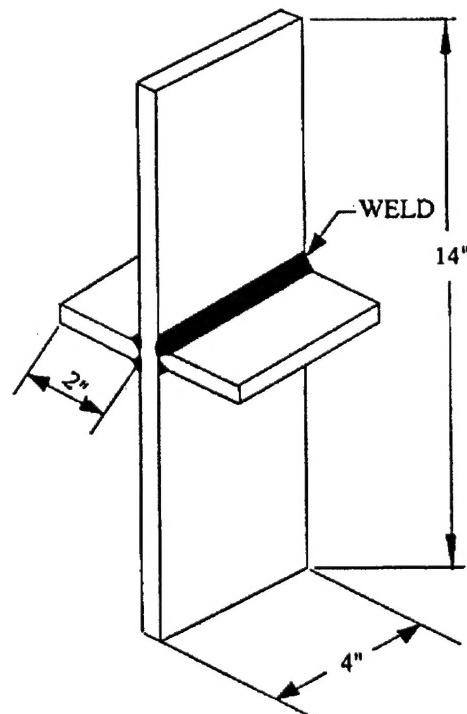
Figure 3. Stainless steel cruciform specimen (dimension in inch)
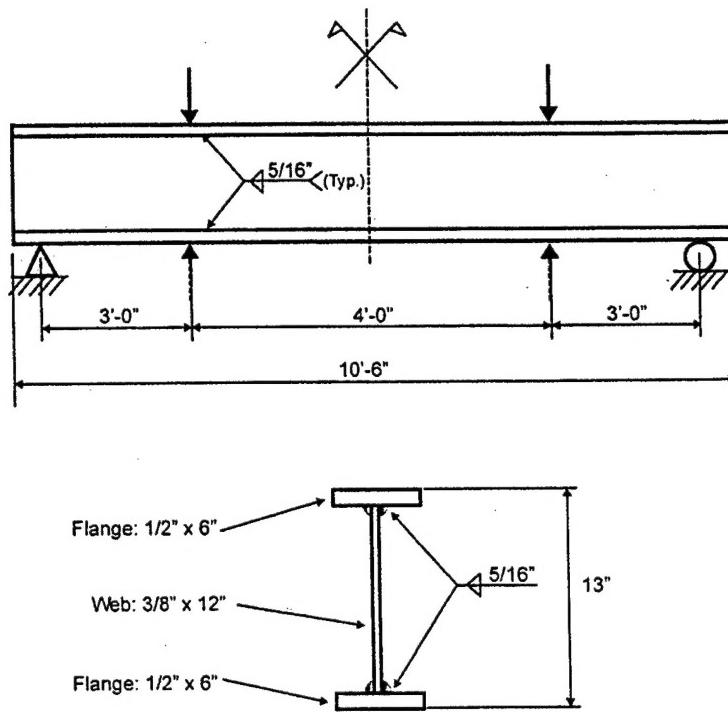
Figure 4. Schematic of Stainless steel beam testing (dimension in inch)

Figure 5, below, shows the technical approach. The basic idea was to create a finite element model of the sample and try to simulate the material properties and initial state of the structure as close to the reality as possible. Afterward, the experimental records and numerical analysis results were put together, and a hybrid automatic learning system was used to extract the data patterns embedded in the database.

```
┌─────────────────────────────────────────────────────┐
│              Fatigue Failure Data Resource            │
├─────────────────────────────────────────────────────┤
│   • Geometry                  • Load                  │
│   • Material Properties       • S-N curves            │
│   • Stress Fields             • Recorded Failure Data │
└─────────────────────────────────────────────────────┘
```

```
┌───┐
│   Database of Physics-Based Descriptors   │
├───┤
│   • Numerical Analysis Model   • Loading History Data│
│   • Tensile/Cyclic Strength   • S-N Curve Constants │
│   • Stress Contours at Hot Points • Load Cycles at Failure │
├───┤
│   Consistent and Clear Format for All Data Sets│
└───┘
```

```
┌─────────────────────────────────────────────────────┐
│                 Automatic Learning Tools              │
├─────────────────────────────────────────────────────┤
│ • Multi-Layer Perceptron Network  • Group Method of Data Handling │
│ • Probabilistic Neural Network    • Learning Expert System │
│ • Genetic Algorithms              • Principal Components Analysis │
│ • Statistical Analysis Software   • Other Automatic Learning Tools │
└─────────────────────────────────────────────────────┘
```

```
┌─────────────────────────────────────────────────────┐
│   • Mathematical Relations between Descriptors        │
│   • In Forms of Polynomials, Rules, or Weights        │
│   • Use Independent Data Sets to Test Confidence Level │
└─────────────────────────────────────────────────────┘
```

```
                 < Results Satisfactory? >
```

```
┌─────────────────────────────────────────────────────┐
│ • Quantitative Representation of Knowledge about Fatigue Failure │
│ • Prediction of Fatigue Failures for More Structures  │
│ • Classification Based on Probabilities of Structural Failure │
└─────────────────────────────────────────────────────┘
```

Figure 5. The fundamental technical approach

For small specimens, 2-D numerical analysis was usually sufficient; but for large structures, it was necessary to do a general 3-D analysis at first, then make refine mesh around the critical zones. Once satisfactory finite element computation was done, a *window* with fixed size was used to tour around the model and collect data at the sites where cracking may occur (see Figure 6). A standard procedure for the construction of three-dimensional finite element models, sub-structuring of large structures and discreet representation of stress/strain contours has been developed, tested and refined. It will be continuously improved as we apply it to more samples.
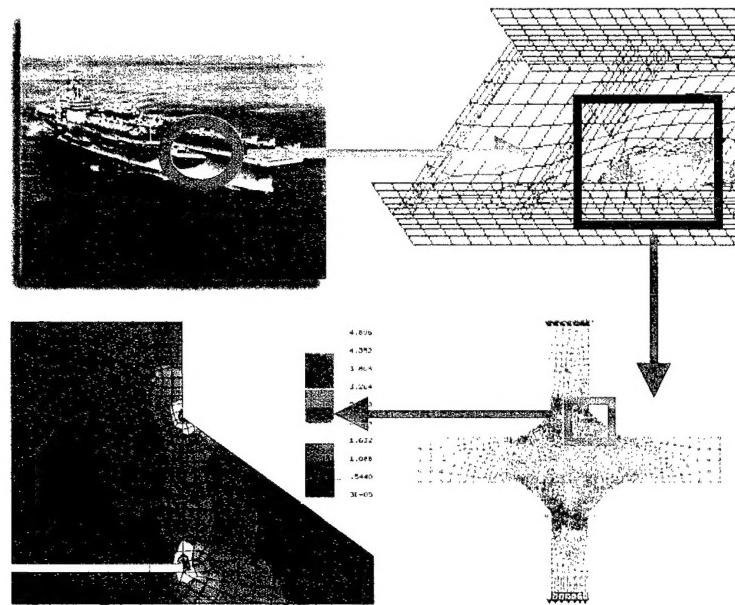
Figure 6. The procedure to make mesh refinement and add windows around the hot points

Inside the windows, we computed the physics-based descriptors to describe the stress field, such as the first invariant I_1, the second invariant J_2 of the stress tensor and the gradient of J_2. We treated all cases in the same way, no matter whether it was a small specimen or a possible failure site in a large welded structure. *Therefore, this approach is applicable to any structural reliability problem as long as the basic failure mechanism is the same.* 724 data sets have been generated based on the experimental records and the numerical analyses.

Technical Approach II (Results of Automatic Learning)

After the data sets representing all the potential cracking sites were generated, the database was organized and submitted to an automatic learning system to extract the mathematical formulas. Several different automatic learning tools have been tested, compared, and combined in a systematic way to produce the best result. We found that the best way was to conduct a simple principal component analysis first to determine the proper mathematical dimensionality, then use learning expert system, neural networks, and statistical analysis software tools to investigate the database in parallel. Training of nerual networks and statistical analysis software to predict fatigue life expectancy are shown in figures 7 and 8. The primary training base was the actual cracking failures recorded in the fatigue tests. After the training, we applied

the obtained formulas to all the data sets, and combined the results on the data sets from the same sample together to make the prediction for every specimen.
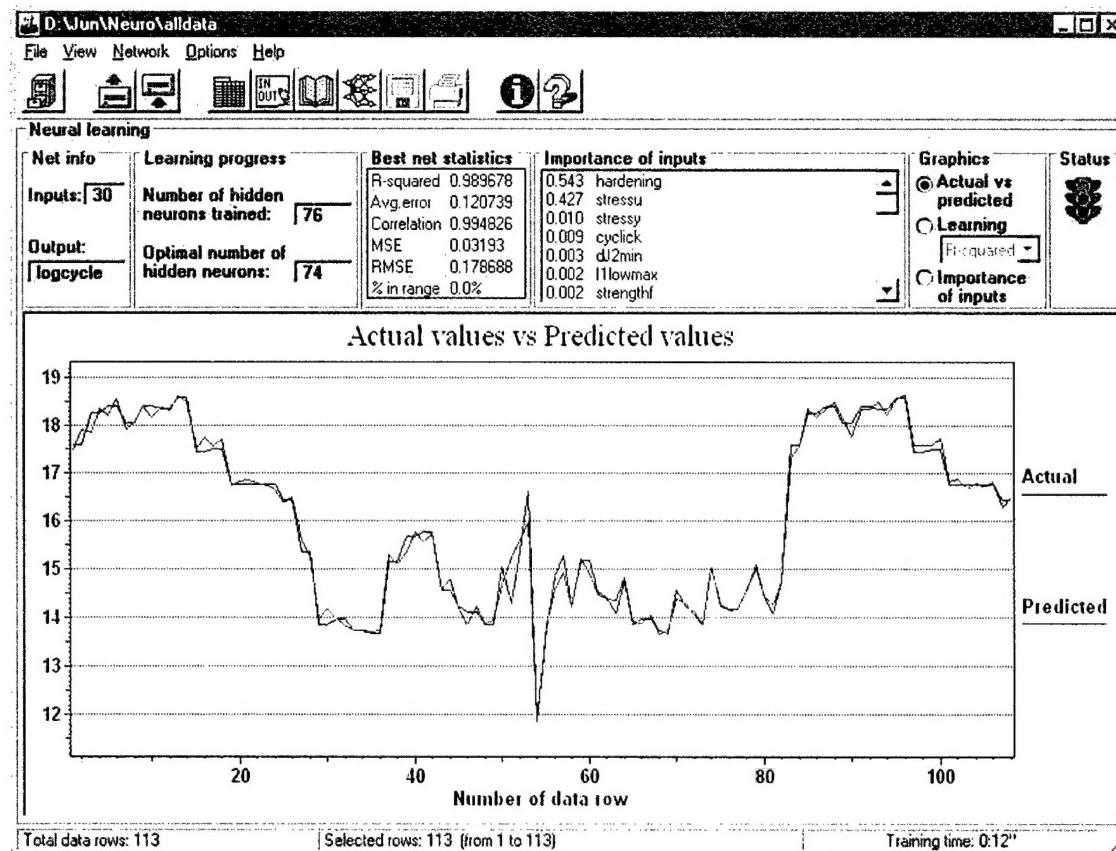

Figure 7.   Predicted value vs. real value during training of a neural network

## All data Life Regression Analysis — — Use Log of Fatige Life

```
logcycle = 22.672 -0.0155 mean_stress -88.079 stressu +93.995 stressy -0.0085 I1highmax
          +0.0068 J2highmax -0.0012 gradJ2highmax +0.0305 I1lowmax +0.0065 J2lowmax
          -0.0015 gradJ2lowmax +0.0071 dJ2max +0.0005 I1highave -0.0128 J2highave
          +0.0049 gradJ2highave -0.0274 I1lowave -0.0626 J2lowave +0.0017 gradJ2lowave
          +0.0204 dJ2ave +0.0035 I1highmin +0.0021 J2highmin -0.0074 gradJ2highmin
          +0.0048 I1lowmin +0.0633 J2lowmin -0.0224 gradJ2lowmin -0.0249 dJ2min
```
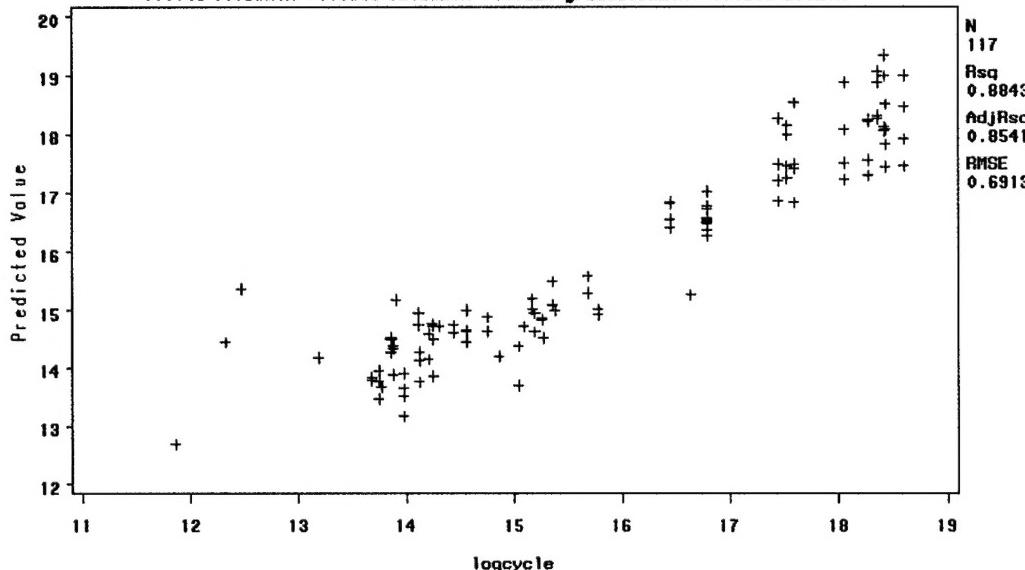

Figure 8. Predicted value vs. real value during statistical analysis

Table 1 shows the results of identifying the more dangerous areas in structures. In this test, 200 data sets were randomly selected from the 724 data sets to train the learning expert system, and the rules correctly classified 99 of the 117 actual failures and 421 of the 607 actual non-failures.

		Prediction	Prediction	
		Yes	No	Total
Actual	Yes	99	18	117
Actual	No	186	421	607
	Total	285	439	724

Table 1. Classification results for all available data sets

We computed both the minimum values and the average values of the projected fatigue lives generated on data sets from the same sample for all the samples we used. The results are shown in table 2. In most cases, the actual fatigue lives of the samples are between the minimum and the average predicted values. It has been observed that when the specimen was under a lot of distortion or induced bending, the minimum value is closer to the actual fatigue life of the specimen; when only a small amount of distortion or induced bending was present, the average value is closer to the actual fatigue life of the sample.

Index	Minimum prediction	Real life	Average prediction
A36 Beam1	23258184	43600000	56775579
A36 Beam2	33696360	69500000	62925495
A36 Beam3	23155309	37800000	41010332
A36 Beam4	12257823	14000000	16716365
Detail 20 H1	1733313	4673522	9249743
Detail 20 H2	1427683	3881143	9625265
Detail 20 H3	1445327	6515677	9466537
Detail 20 H4	1637240	7136458	9863144
Detail 20 H5	1402929	2099552	9474762
Detail 20 H6	657467	1529241	9104450
Detail 20 H7	829150	1357643	2894670
Detail 20 H8	897866	1044729	3111631
Detail 20 H9	643478	3421866	2628742
Detail 20 H10	848253	1064917	2577045
Detail 20 H11	24426	1170904	985429
Detail 20 H12	21049	928648	911771
Detail 20 H13	249021	873131	1099722
Detail 20 Q1	1202001	1544382	5689469
Detail 20 Q2	645754	1473724	4410507
Detail 20 Q3	1396844	3971989	16749212
Detail 20 Q4	1619445	2094505	17208501
Detail 20 Q5	1408498	3573276	17878221
Detail 20 Q6	589243	1862343	20609426
Detail 20 Q7	1765098	1347549	17496340
Detail 20 Q8	1523587	2553782	19891723
AL-6XN Cruciform 1	1159224	1632800	1159224
AL-6XN Cruciform 2	1504631	4796700	1504631
AL-6XN Cruciform 3	1952239	16885300	1952239
AL-6XN Cruciform 4	30484	2500	30484
AL-6XN Cruciform 5	144678	141900	144678
AL-6XN Cruciform 6	409091	956800	409091
AL-6XN Cruciform 7	688784	2850800	688784
AL-6XN Cruciform 8	941700	4292000	941700
AL-6XN Beam1[*]	5137074	260840	6534934
AL-6XN Beam2[*]	5842535	1094500	6296885
AL-6XN Beam3[*]	3908833	224600	4945196
AL-6XN Beam4[*]	5032045	4253000	5925563
AL-6XN Beam5[*]	3360823	532300	4686518

Table 2. Predicted fatigue lives of the samples vs. the actual fatigue lives

It is notable that the predicted lives of A36 beams are quite accurate, and most of the predicted fatigue lives are conservative, but the predicted lives of AL-6XN stainless steel beams are not conservative. We interpret that it shows the finite element modeling of the stainless steel beams is not close enough to the actual testing conditions. This finding, however, demonstrates the self-correcting capability of this approach. It also demonstrates the necessity of closely monitored experimental work and highly tuned modeling to accurately simulate the damage process.

We are confident that, after some improvement, this method can be used as an effective way of computing lower and upper bounds for fatigue failure of structures with substantial crack initiation period.

Impact/ Navy Relevance

Ships consist of heavily welded structures that are regularly exposed to fluctuating loads during their service. Therefore, they are prone to metallic fatigue failure. Welds are of particular importance because they involve stress concentration and residual stresses. Therefore, they are likely to cause fatigue failure. Because of economic reasons, welding technique is widely employed in the construction of ships. This makes the study on fatigue of weld even more important.

Though some methods have already been developed, they generally require assumptions on the geometry, loading conditions, and material properties. Each calculation thus provides only numerical data for one particular case, which provides a limited basis for design decisions. The new approach, which we have used, offers a feasible way to avoid this major difficulty. It allows us to use all existing data, experimental, computational, or theoretical in a unified manner to support the design of structures. It also permits an interactive accumulation of available knowledge and uses the information effectively.

With hundreds of combat and supporting vessels operating in the seas around the world, it is very beneficial for the navy to have state-of-the-art tools to assess the reliability of welded ship structures. Not only can this help reducing the possibility of fatigue-fracture related accidents, but also it may lead to significant savings due to improved guidance of inspection-repair management. The importance of this problem is further reinforced by the fact that many navy ships are required to serve very long lives. The increasing usage of nuclear powered vessels also requires an even higher control over weld reliability due to the danger of potential nuclear leakage.

III. Technology Transfer

Through this project, we have been interacting with researchers from Naval Surface Warfare Center, particularly working with Dr. David Kihl. We have also been interacting with the researchers from Lehigh University's ATLSS center. In addition, we have been collaborating research efforts with Professor Joseph Zarka from Ecole Polytechinique of France. The general approach developed through this project has been used to integrate diverse experimental, theoretical, and computational information, and it has the potential of being developed into a tool with significant practical applications.

50 HSLA-80 steel samples have been transferred to CEAM, and we are going to apply our approach to investigate the fatigue damage of these specimens. We plan to learn more about the details of the fatigue experiments on large-scale beams at Lehigh University so we can improve the accuracy of the predictions. Mr. Jun Huang (graduate student) traveled to Ecole Polytechinique in November 2000, and the procedure to perform 3D numerical analysis has been developed there, and applied here at UCSD. We also plan to introduce a new method of computing equivalent loading history through evaluating accumulative plastic strains. This new approach was developed by Professor Zarka in 2000, and has been refined last year.

IV.   SCIENTIFIC AND TECHNICAL PERSONNEL SUPPORTED BY THIS PROJECT   AND DEGREES AWARDED DURING THIS REPORTING PERIOD

Scientific and Technical Personnel:

Masoud Beizaie (Staff Research Associate): research focusing on the reliability of weldments, especially those used in marine structures. This activity includes extensive literature survey and search for available databases and software.

Joseph Zarka (Visiting Research Scientist from Ecole Polytechnique, France): the research project includes collaboration with Dr. Zarka, who spends at least three months each research year at CEAM of UCSD. The approach, to study the reliability of ship structures and particularly their welded parts, utilizing the automatic Learning Expert System (**L.E.S**), has been developed by Dr. Zarka.

Graduate Research Assistants:

Jun Huang (9/96 - present): research focusing on fatigue and Dr. Zarka's new approach to inelastic analysis and the use of numerical analysis software. The research on fatigue includes examination of micro-mechanisms of fatigue, the influence of non-zero mean stress, the accumulative damage theories and the use of statistics in fatigue. The main idea of the new approach is to solve the plastic problem using elasticity solutions. Extensive comparative analysis has been done utilizing the basic components of NISA.

Degrees Attained: None at this time. It is anticipated that Jun Huang will receive his Ph.D. Spring 2003.

V. ONR Database statistics for reporting period (July 1, 01-Feb.02)
Number of Papers Published in Refereed Journals Citing ONR Support: 0
Number of Papers in Press in Refereed Journals Citing ONR Support: 0
Number of Books or Chapters Published Citing ONR Support: 2
Number of Books or Chapters in Press Citing ONR Support: 0
Number of Technical Reports & Non-Refereed Papers: 7
Number of Invention Disclosures Citing ONR Support: 0
Number of Patents Granted Citing ONR Support: 0
Number of Patents Pending Citing ONR Support: 0
Number of PI/COPI's:
Total: 1
Women:0
Minorities:0
Number of Grad Students:
Total: 1
Women:0
Minorities:0
Number of Post Docs:
Total: 0
Women:0
Minorities:0

VI. Journal Publications Appearing in Print (for reporting period July 1, 01-Feb.02)

- Zarka, J. and H. Karaouni, "Fatigue Analysis during One-parametered Loadings", In Proceedings of First MIT conference on computational fluid and solid mechanics, 12-15 June 2001, Cambridge, USA. Appears in Conference Proceedings published by Elsevier Science, Oxford, UK, (2001) p.559.

- Zarka, J. and H. Karaouni, "Fatigue analysis of welded structures during random loadings", Proceeding of the 9th National Congress on Theoretical and Applied Mechanics, Bulgaria, *Theoretical and Applied Mechanics,* edited by Y.A. Ivanov A. Baltov and E. Manoach (2001) 153-165.

VII Non-Refereed Publications and Published Technical Reports (for reporting period July 1, 01-Feb.02)

- Karaouni, H. (2001), "Nouveaux outils pour la conception fiable des structures", Thèse de doctorat, Ecole Polytechnique, December, France.

- J. Zarka, "Fatigue Analysis of Welded Structures during Random Loadings," Proceedings of 9th National Congress on Theoretical and Applied Mechanics, Varna, Bulgaria, Sept. 19-22, 2001.

- Zarka, J. and H. Karaouni, "Fatigue Analysis of Structures during Random Loadings", Proceedings of Second International Conference on Theoretical, Applied, Computational and Experimental Mechanics, IIT Kharagpur 27-30 December 2001 (2001). Distributed by Conference via CD.

VIII. Books (and sections thereof) Published: None

IX. Presentations (for reporting period July 1, 01-Feb.02)

a.   Invited:

- J. Zarka, *Keynote Lecture* "Fatigue Analysis of Welded Structures during Random Loadings," 9th National Congress on Theoretical and Applied Mechanics, Varna, Bulgaria, Sept. 19-22, 2001.

- J. Zarka, *Keynote Lecture* "Fatigue Analysis of Welded Structures during Random Loadings," 2nd International Conference on Theoretical, Applied, Computational and Experimental Mechanics, IIT, Kharagpur, India, December 27-30, 2001.

- J. Zarka and H. Karouni, Keynote Lecture, "Towards an Optimal reliability of Metallic Structures during Random Loadings," ASEM'02, Korea.

b.   Contributed:

- Zarka, J., Doux, T., "Multidisciplinary Optimal Design of Woven Composites," Symposium Mechanics of Advanced Composites, 2001 Mechanics and Materials Summer Conference, San Diego, June 27-29 2001.

- Zarka, J., "Fatigue analysis during multi-parametered random loadings", Workshop at Laboratoire Mécanique des Solides (LMS), Ecole Polytechnique, June, France (2001).

X. Other Sponsored Science and Technology July 1, 01-Feb.02

"Damage Tolerant Lightweight Armor Materials," ARO DAAH-04-96-1-0376; $1,500,000; 8/15/96 - 8/02.

"Computational Modeling of Strain Localization in Frictional Granular Materials," NSF Grant CMS-9729053; $247,741; 1/1/99-12/31/03.

"Defense University Research Instrumentation Program to Develop Special CCD Camera for Full-Field Time-resolved Data Acquisition for High-Rate Deformation," ARO DAAD19-99-1-0079, Total awarded $219,255 for period 3/31/99 - 3/31/01 (includes 12 month NCE).

"Experimental and Microstructural Characterization, and Physically-Based Micromechanical Modeling of Ionic Polymer Metal Composite," Naval Research Laboratory Grant No. MDA972-00-1-0004, Total Awarded $692,000 for period 3/6/00-3/5/03, Y1: 201,340, Y2: 280,600, Y3: 210,060.

"Special X-Ray Camera Facility for Full-Field Time-Resolved Data Acquisition for High-Rate Deformation," ARO AMXRO-ICA DURIP DAAD19-00-1-0059, Defense University Research Instrumentation: Total Amount Funded $106,163 for period 3/31/00-3/30/02 (includes 12 month NCE).

"Multiscale Multifunctional Materials," ARO/DARPA DAAD19-00-1-0525, Total amount awarded $2,535,427.00 for period 4/01/00-3/31/04.9/1/00 Period A: 2 months $50,000, Period 1: 12 months $451,816, Period 2: 12 months $495,865, Period 3: 10 months $510,139, Period 4 (sub option): 12 months $502,607.

"Fatigue Failure of Hybrid Polymer Composite-Metal Joints," ONR N00014-02-1-0420: Total Amount Awarded $94,379.00 for period March 08, 2002 - March 97, 2003. Ist Increment: $67,000.

"Adaptive Materials for Energy-Absorbing Hybrid Structures," ONR/MURI N00014-02-1-0666: Total Amount Awarded 2,500,000.00 for period May 1, 2002 - April 30, 2007. Co-PI's Ken Vecchio, Minoru Taya (U. of Washington) and K. Bhattacharya (Caltech).

XI.   COMPLETE LIST OF PUBLICATIONS AND PRESENTATIONS

(April 1996 - June 2002)

Books: Published:

Zarka, J., J. Frelat, G. Inglebert and P. Navidi, *Practical Analysis of Inelastic Materials and Structures*, Vol. 1: Simple Solutions for Classical Formulations, Kluwer Press, 2000.

Zarka, J., P. Navidi, M. Terrien and M. Sebag, *Practical Analysis of Inelastic Materials and Structures*, Vol. 2: Intelligent Optimal Design , Kluwer Press, 2000.

Journal Publications Appearing in Print:

- Zarka, J., and P. Navidi, "Conception Optimale Intelligente des Materiaux et des Structures," Proceedings of Intl. Conf. EMT'97, *Engineering Mechanics Today*, Hanoi 1-3 Aug. 1997.

- Zarka, J. and P. Navidi, "Intelligent Modeling of Materials," *Mechanics of Materials*, Vol. 28 (1998) 61-82.

- Nemat-Nasser, S., W-G. Guo, D. P. Kihl, "Thermomechanical response of Al-6XN stainless steel over a wide range of strain rates and temperatures," *JMPS*, Vol. 49 (2001)1823-1846.

- Zarka, J. and H. Karaouni, "Fatigue Analysis during One-parametered Loadings", In Proceedings of First MIT conference on computational fluid and solid mechanics, 12-15 June 2001, Cambridge, USA. Appears in Conference Proceedings published by Elsevier Science, Oxford, UK, (2001) p.559.

- Zarka, J. and H. Karaouni, "Fatigue analysis of welded structures during random loadings", Proceeding of the 9th National Congress on Theoretical and Applied Mechanics, Bulgaria, *Theoretical and Applied Mechanics,* edited by Y.A. Ivanov A. Baltov and E. Manoach (2001) 153-165.

Non-Referred Publications and Published Technical Reports:

- Huang, J., J. Zarka and P. Navidi, "A New Approach in Reliability of Welded Structures," Engineering Mechanics: A Force for the 21st Century, *Proceedings of the 12th ASCE Engineering Mechanics Conference*, May 1998, La Jolla, CA. (1998), 1521-1524.

- Zarka, J., J. Huang and P. Navidi, "A New Approach in Reliability of Welded Structures," *Proceedings of the 6th International Conference on Nuclear Engineering, ICONE-6*, May 1998, San Diego, CA.

- Zarka, J. and P. Navidi, "Fusion of Experimental Results During Stress Corrosion Tests," *Proceedings of the 6th International Conference on Nuclear Engineering, ICONE-6*, May 1998, San Diego, CA.

- Zarka, J., "Addicted to Manufacturing!," *Proceedings of Detroit SAE Conference*, May, 1998.

- Zarka, J. and P. Navidi, "New Method for Fatigue and Stress Corrosion Damages," *Proceedings of PVP-Vol. 366 Technologies in Reactor Safety, Fluid-Structure Interaction, Sloshing and Natural Hazards Engineering*, ASME, (1998) 13-20.

- Zarka, J., P. Navidi, S. Nemat-Nasser and J. Huang, "Towards a New Vision of Reliability of Welded Structures," *Proceedings of OMAE'98*, Lisbon, Portugal, July 5-6, 1998. (To be printed in OMAE'99 Proceedings).

- Zarka, J., "Intelligent Optimal Design: What Does it Mean?" *Proceedings of the Polish Conference in Solid Mechanics*, Zakopane, Poland, August 30-September 5, 1998.

- Zarka, J., P. Navidi, S. Nemat-Nasser and J. Hung, "Design of Reliable Structures: A New Approach," *Proceedings of EUROMECH 385*, Aachen, Germany, September 8-11, 1998.

- Zarka, J. and T. Doux, "Optimal Design of Textile Woven Composite Materials," Proceedings of 4th International Conference on Constitutive Laws for Engineering Materials: Experiment, Theory, Computation and Applications, Rensselaer Polytechnic Institute, Troy, NY, USA, July 27-30, 1999.

- Zarka, J., H. Karaouni, S. Nemat-Nasser, and J. Huang, J. "Fatigue analysis of welded structures", SMIRT 15 - PCS 13, Intelligent Software Systems in Inspection and Life Management of Power and Process Plants, August (1999).

- Zarka, J., P. Navidi, H. Karaouni, S. Nemat-Nasser and J. Hung, "Fatigue Analysis of Welded Structures," *International Post-SMIRT Conference on Intelligent Software Systems Inspection and Life Management of Power and Process Plants*," Korea, September,1999.

- Zarka, J., "Intelligent Numerical Simulations in Engineering Problems," Proceedings of 9th International Colloquium on Numerical Analysis and Computer Science with Applications, Plovdiv, Bulgaria, August 12-17, 2000.

- Zarka, J. and J.M. Hablot, "Intelligent Optimal Adaptive Mesh During Inelastic Analysis of Structures," Proceedings of 2000 ASME DETCOO: 26th Design Automation Conference, Baltimore, MD, September 10-13, 2000.

- Zarka, J. and T. Doux, "Intelligent Optimal Design of Woven Composites'" Proceedings of 2000 ASME DETCOO: 26th Design Automation Conference, Baltimore, MD, September 10-13, 2000

- Zarka, J., "Optimal Design of a Beam," Proceedings of American Institute of Aeronautics and Astronautics 8th AIAA/USAF/NASA/ISSMO Symposium on Multidisplinary Analysis and Optimization, Long Beach, CA, September 6-8, 2000.

- Zarka, J. and T. Doux, "Intelligent Modeling of Woven Materials," Proceedings of American Institute of Aeronautics and Astronautics 8th AIAA/USAF/NASA/ISSMO Symposium on Multidisplinary Analysis and Optimization, Long Beach, CA, September 6-8, 2000.

- Zarka, J., "Intelligent optimal design of naval structures: Is it possible ?", SIM OUEST 2000, Marine Technology: Industry & Simulation, 29-30 November 2000, Keynote invited lecture, France. Distributed by SIM QUEST via CD of Proceedings (2000).

- Zarka, J. and H. Karaouni, "Fatigue Analysis During One-parametered Loadings," Proceedings of First M.I.T Conference Computational Fluid and Solid Mechanics, Cambridge, June 2001.

- Karaouni, H. (2001), "Nouveaux outils pour la conception fiable des structures", Thèse de doctorat, Ecole Polytechnique, December, France.

- J. Zarka, "Fatigue Analysis of Welded Structures during Random Loadings," Proceedings of 9th National Congress on Theoretical and Applied Mechanics, Varna, Bulgaria, Sept. 19-22, 2001.

- Zarka, J. and H. Karaouni, "Fatigue Analysis of Structures during Random Loadings", Proceedings of Second International Conference on Theoretical, Applied, Computational and Experimental Mechanics, IIT Kharagpur 27-30 December 2001 (2001). Distributed by Conference via CD.

Presentations
a.   Invited:

- Nemat-Nasser, S., J. Zarka, P. Navidi, M. Bezaie and A. Azhdari, "Fatigue Failure Prediction Using Automatic Learning," Presented at the Joint ASME/ASCE/SES Meeting Northwestern University, IL, Symposium on Damage Mechanics in Engineering Materials, June 29-July 2, 1997.

- Zarka, J., "Intelligent Optimal Design: What does it Mean?" Polish Conference in Solid Mechanics 98, Zakopane, Poland, August 30-September 5, 1998.

- Zarka, J., "Intelligent Modelling of Composite Materials," Aachen University, Aachen, Germany, September 9, 1998.

- Zarka, J., "Ready for Intelligent Optimal Design?" The School of Civil Engineering Structural Engineering and Construction Program, Bangkok, June, 20, 2000.

- Zarka, J. "intelligent Fatigue Analysis of Welded Structures," Mechanical Engineering Seminar, Northwestern University, Evanston, December 7, 2000.

- Zarka, J., "Intelligent Optimal Design of Woven Composites," RPI, Troy, December 11, 2000.

- Zarka, J., "Intelligent Optimal Design With a Direct Link to CAD," Seminars in Robotic Mechanical Systems, McGill University, CANADA, January 15, 2001.

- Zarka, J., "New Vision of the Reliability of Structures" Institute of Nuclear Energy Technology, Tsinghua University, March, 23, 2001.

- Zarka, J., "Intelligent Optimal Design of Composites," Cambridge University Engineering Department, May 18, 2001.

- Zarka, J. and , H. Karaouni, "Fatigue Analysis during One-parametered Loadings," First M.I.T Conference Computational Fluid and Solid Mechanics, Cambridge, June 2001.

- Zarka, J., Doux, T., *Keynote presentation*: "Intelligent Design of Woven Composites," Symposium on Experiments and Modeling of Failure of Modern Materials-In Honor of Sia Nemat-Nasser, 2001 Mechanics and Materials Summer Conference, San Diego, June 27-29 2001.

- J. Zarka, *Keynote Lecture* "Fatigue Analysis of Welded Structures during Random Loadings," 9th National Congress on Theoretical and Applied Mechanics, Varna, Bulgaria, Sept. 19-22, 2001.

- J. Zarka, *Keynote Lecture* "Fatigue Analysis of Welded Structures during Random Loadings," 2nd International Conference on Theoretical, Applied, Computational and Experimental Mechanics, IIT, Kharagpur, India, December 27-30, 2001.

- J. Zarka and H. Karouni, Keynote Lecture, "Towards an Optimal reliability of Metallic Structures during Random Loadings," ASEM'02, Korea.

b.   Contributed:

- Zarka, J., and P. Navidi, "Conception Optimale Intelligente des Materiaux et des Structures," presented at Intl. Conf. EMT'97, *Engineering Mechanics Today*, Hanoi 1-3 Aug. 1997.

- Zarka, J., and P. Navidi, "Optimal Design of Reliable Structures," presented at SMIRT: Post Conference Seminar N 13, Paris, Aug. 25-27, 1997, Intelligent Software Systems in Inspection and Life Management of Power and Process Plants.

- Huang, J., J. Zarka and P. Navidi, "A New Approach in Reliability of Welded Structures," ASCE Engineering Mechanics Conference, May 1998, La Jolla, CA.

- Zarka, J., P. Navidi and J. Huang, "A New Approach in Reliability of Welded Structures," 6th International Conference on Nuclear Engineering, ICONE, May 1998, San Diego, CA.

- Zarka, J. and P. Navidi, "Fusion of Experimental Results During Stress Corrosion Tests," 6th International Conference on Nuclear Engineering, ICONE, May 1998, San Diego, CA.

- Zarka, J., "Addicted to Manufacturing!" Detroit SAE Conference, May, 1998.

- Zarka, J., P. Navidi, S. Nemat-Nasser and J. Huang, "Towards a New Vision of Reliability of Welded Structures," OMAE'98, Lisbon, Portugal, July 5-6, 1998.

- Zarka, J., "Design of Reliable Structures: A New Approach," EUROMECH 385, Aachen Germany, September 8-11, 1998..

- Zarka, J. and T. Doux, "Optimal Design of Textile Woven Composite Materials," Proceedings of 4th International Conference on Constitutive Laws for Engineering Materials: Experiment, Theory, Computation and Applications, Rensselaer Polytechnic Institute, Troy, NY, USA, July 27-30, 1999.

- Zarka, J., P. Navidi, H. Karaouni, S. Nemat-Nasser and J. Hung, "Fatigue Analysis of Welded Structures," *Proceedings of International Post-SMIRT Conference on Intelligent Software Systems Inspection and Life Management of Power and Process Plants*," Korea, September, 1999.

- Zarka, J., "Intelligent Numerical Simulations in Engineering Problems," 9th International Colloquium on Numerical Analysis and Computer Science with Applications, Plovdiv, Bulgaria, August 12-17, 2000.

- Zarka, J. and J.M. Hablot, "Intelligent Optimal Adaptive Mesh During Inelastic Analysis of Structures," 2000 ASME DETCOO: 26th Design Automation Conference, Baltimore, MD, September 10-13, 2000.

- Zarka, J. and T. Doux, "Intelligent Optimal Design of Woven Composites'" 2000 ASME DETCOO: 26th Design Automation Conference, Baltimore, MD, September 10-13, 2000.

- Zarka, J., "Optimal Design of a Beam," American Institute of Aeronautics and Astronautics 8th AIAA/USAF/NASA/ISSMO Symposium on Multidisiplinary Analysis and Optimization, Long Beach, CA, September 6-8, 2000.

- Zarka, J. and T. Doux, "Intelligent Modeling of Woven Materials," American Institute of Aeronautics and Astronautics 8th AIAA/USAF/NASA/ISSMO Symposium on Multidisplinary Analysis and Optimization, Long Beach, CA, September 6-8, 2000.

- Zarka, J., "Intelligent Optimal Design of Naval Structures: Is it Possible?" SIM Quest 2000, European Conference, Marine Technology Industry and Simulation, Nates, France, November 29&30, 2000.

- Huang, J., "A New Approach to Structural Reliability In Fatigue Failure Based On Automatic Learning," 2001 Mechanics and Materials Summer Conference, San Diego, June 27-29 2001.

- Zarka, J., Doux, T., "Multidisciplinary Optimal Design of Woven Composites," Symposium Mechanics of Advanced Composites, 2001 Mechanics and Materials Summer Conference, San Diego, June 27-29 2001.

- Zarka, J., Karaouni H., "Fatigue Analysis During One-Parameter Loadings," First M.I.T Conference of Computational Fluid and Solid Mechanics, Cambridge, June 2001.

- Zarka, J., "Fatigue analysis during multi-parametered random loadings", Workshop at Laboratoire Mécanique des Solides (LMS), Ecole Polytechnique, June, France (2001).

Final Technical Report
and EOYFL July 1, 01- February 28, 02.

18